Science Driven Assessment of Needs for Marine Sediment Coring 2015-2025

Report of Coring Needs Workshop
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Executive Summary

Sediment coring supports high impact science in a diverse array of disciplines in the geosciences. Access to reliable coring systems is essential for addressing a number of critical questions of both scientific and societal importance, including almost all of the scientific priorities outlined in the Decadal Survey of Ocean Sciences. Despite the continued importance of sediment coring technologies, there is widespread community concern that there has been an erosion of sediment coring capability available to the U.S. research community.

Based on the responses to a community survey and discussions during a workshop convened at the National Science Foundation in May 2015, we present a ranked list of priorities for coring infrastructure in the coming decades:

1) The ability to deploy short (gravity and multi-core) coring systems from all Global, Ocean and Regional Class vessels
2) The development of a robust and portable Jumbo Piston Coring system that is capable of deployment on all Global and Ocean Class vessels and capable of collecting cores of up to 20 m length over the full range of ocean depths
3) Regaining the capability of collecting cores of up to 45 m length on a large research vessel
4) Exploration and development of alternative mechanisms for sediment coring and drilling, particularly those that enable the collection of sediments to a depth of 100 m or more below seafloor.

It is essential that we make the needed investments in current coring technologies and resources so that they can be used efficiently, reliably and safely. This will include ensuring that ships are configured to deploy the coring apparatus, and that appropriate, up-to-date supporting infrastructure such as winches, wires and cranes are available. Investments in training and development of both the scientific user and technical support communities will also be necessary to ensure both the reliable and efficient operation of existing systems and the development of new approaches and technologies.

Introduction

Coring of deep-sea sediment probably began as a consequence of deep-sea sounding with weights. In very deep water there was no way to determine the bottom had been reached so early bathymetric work adapted a small tube or cup to a weight (often a cannonball) and recovered mud was proof that the bottom had been reached. The HMS *Challenger* expedition of 1874-1876 took the first cores by use of a tube that projected 45 cm from the bottom of the weight and often recovered cores of about 30 cm. However, at many locations the sediment was probably Holocene and the recovered cores did not stimulate interest in ocean history. Fifty years later the *Meteor* expedition to the South and Equatorial Atlantic sampled the seafloor with a 3 m corer. From those core samples, Schott proposed that changes between warm and cold planktonic foraminiferal fauna represented changes in Pleistocene climate. In 1936, Western Union Telegraph Co.'s cable laying ship *Lord Kelvin* conducted what was probably the first trans-Atlantic geosciences transect, from Newfoundland to Ireland. The 11 cores, up to 3 m long, were taken by C. S Piggot for his study of radioactivity in sediments, and employed an explosive charge to drive the pipe into the sediment. Sampling and study of the sediments by Bramlette and Bradley in 1940 recognized most of the topics we study today in North Atlantic paleoceanography, including foraminiferal changes, volcanic ash zones, ice rafted debris zones, glacial stages and substages, Milankovitch theory, and bottom current activity. Bramlette and Bradley compared their results to the earlier results of Schott, and had it not been for World War II, studies of marine sediments might have been ten years more advanced. The first important post-war development in coring technology was the invention of the piston corer by Kullenberg, and its application by the Swedish Deep-Sea Expedition of 1947-1948. This is generally thought to represent the birth of paleoceanography. That expedition was followed in the 1950s by plans to drill the Moho, and in the 1960s by the beginning of the Deep Sea Drilling Project.

The purpose of this report, and the workshop on which it is based, is to define the current and future needs for seafloor sediment sampling technology, especially piston coring. This is prompted by several recent events, including the retirement of two Global Class research vessels, the recent or imminent delivery to the fleet of three new large research vessels (one Global and two Ocean Class), and the recent release of the Decadal Survey of Ocean Sciences (DSOS) report. R/Vs *Melville* and *Knorr*, active in the fleet since 1969 and 1970, respectively, were oceanographic workhorses for more than 40 years. They were capable of operating in all oceans, and could serve a scientific party of 32. In 1991 these ships were overhauled and lengthened to 279 ft (85 m). About a decade ago R/V *Knorr* was strengthened to handle a long (40 m) piston corer with considerable improvements over existing corers of that length. Of the new ships, Global Class R/V *Sikuliaq* (261 ft, 24 science berths) was designed for Arctic research, and Ocean Class R/Vs *Neil Armstrong* and *Sally Ride (*238 ft. with 24 science berths) were designed as replacements for R/Vs *Melville* and *Knorr*. There is justifiable concern that none of these new ships, as presently configured, are as suitable for piston coring as the ships they replace. There is also concern that the range of operations of currently configured piston coring systems is limited by the ability to safely pull cores out of sediments without exceeding permissible tension on the wire.

The DSOS report examined the state of all ocean science disciplines in light of the need to balance basic science with the costs of operation and maintenance of research facilities. DSOS concluded that, in a time of declining or level funding, the best way to realign core science spending with respect to facilities spending within NSF's Ocean Sciences Division (OCE) is to make cuts to major facilities, including a 5% cut to the UNOLS fleet. Against this background of overall cuts in infrastructure spending, it is expected that the new research vessels will need some expensive modifications to make it possible to safely launch and recover sediment cores of at least 20 m length. Therefore, the charge to workshop attendees was to (i) identify the high priority science driving the need for relatively long piston cores (at least 20 m), and (ii) outline the general coring needs for the coming decade.

About a month before the workshop, the OCE community was invited to complete an online survey about their experience coring on UNOLS ships, their use of piston core sediments from various archives, and the nature of their research. 125 responses were received from scientists in 26 states and 61 institutions. Survey responses reflected widespread support for the continued collection of piston cores by the U.S. research fleet from scientists covering a broad base of research areas. The workshop participants appreciated the detailed and thoughtful comments and worked to incorporate the views of the community into the recommendations that are detailed in this report. The complete survey responses are included as an appendix to this report (Appendix A).

With these encouraging results, the workshop was held at the National Science Foundation on 28-29 May 2015. Twenty people attended in person and one participated via conference call. Participants included 15 NSF principal investigators, two marine coring experts, and four agency personnel (NSF, USGS, ONR and a representative from the UNOLS office. The committee was organized to ensure representation from a variety of institutions and to include a diverse set of PIs representing different career stages, levels of experience with coring, and scientific interests. Meeting attendees presented diverse examples of important research using piston cores, and the practical issues involved with piston coring from UNOLS vessels (Appendix B: Workshop Agenda). All workshop participants contributed to the writing of this report.

Scientific Rationale for Coring

Sediment coring supports high-impact science in a diverse array of disciplines in the Earth sciences (*Figure 1*). Piston coring has been central to the development of the fields of Paleoceanography and Paleoclimatology, providing marine sediments for time series of climate and environmental change from chemical, isotopic, micropaleontologic, and other studies. These studies provide information on mechanisms for climate change, and the sensitivity of the Earth system to changes in climate forcings. Piston coring in the 1970s and 1980s established the ocean's central role in Pleistocene ice ages, and put these changes into a theoretical framework that links small variations in the Earth's orbit to global climate change. The paleoceanographic tool kit now contains methods that reliably record past ocean surface temperatures to an accuracy of ~± 1ºC, past density structure on a 3-dimensional basis, and changes in deep circulation patterns as evidenced by chemical and biogeochemical tracers. These records have the potential to reveal decadal, centennial, and millennial oceanic processes that lie outside the short range of modern oceanographic instrumental time series.

Marine sediments also integrate the marine and terrestrial biosphere on a variety of time scales. While fossils collected from sediment cores have been enormously useful in reconstructing the changes in ecosystems through time, more recently the analysis of molecular biomarkers from near-shore sediment cores has opened new possibilities for the detailed reconstruction of past vegetation and hydrologic change. Continued acquisition of new cores is critical for the emerging field of biomarker analysis as older core handling and storage methods contaminated the organic fraction of the sediments.

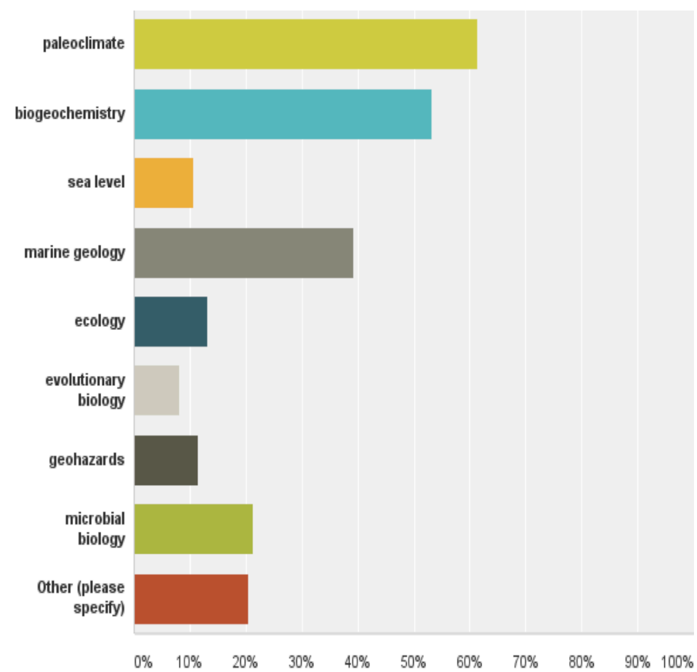

Figure 1: Responses of the community survey to the question, "What describes your research area?" Respondents were allowed to choose more than one area.

Coring technologies have been critical for understanding of both marine biogeochemical cycling and subsurface life. Because cores capture both the solid and fluid components of the subseafloor environment, they advance understanding of the chemical fluxes through the marine system and the nature of life indigenous to the cored sediment. Pore fluid chemistry from cores underpins the understanding of chemical exchange between the sediment and the ocean, biotic and abiotic chemical transformations within and beneath the sediment, and the resulting marine chemical cycling rates. How these transformations and rates impact chemical transfer between different reservoirs is in turn critical to understand past, present, and future ocean biogeochemistry. Geochemical studies of ocean sediments and pore fluids have also improved understanding of the development and extent of both traditional hydrocarbon reserves and marine gas hydrates. Microbial samples and molecular data from cores have greatly advanced understanding of subsurface ecosystems and the limits to life on Earth. Paired biogeochemical and microbiological studies of cored materials have advanced understanding of how subseafloor microbial communities influence global geochemical cycles. Biogeochemical and microbiological studies have often focused on the top of the sediment column; however, biologists have recently taken advantage of piston-coring technologies to examine subseafloor microbial ecosystems and establish that the biosphere extends deep beneath the ocean floor. The capability to collect long cores (20 meters or greater) that span the full range of ocean depths (0 to 11 km below sea level) will allow us to more fully explore and constrain the microbial biosphere and biogeochemical cycling in subsea sediments.

Studies based on piston coring have also been used to better understand basic problems in the solid earth sciences such as the evolution of ocean basins and the development of continental margins. Sediment records have been instrumental in understanding how the

Earth's magnetic field changes through time, and how heat from Earth's interior is transferred to the surface. They have allowed for the better understanding of subsea sedimentary erosional and depositional processes. Methods are now being further developed to combine information from sediment cores and geophysical sensing techniques to better understand the recurrence of earthquakes and submarine landslides, both of which can generate hazardous tsunamis. Sediment cores also can provide geotechnical information about the nature and strength of subsea sediments. This can inform both studies of hazards such as submarine landslides, and siting of ocean structures such as offshore wind farms or oil drilling platforms.

Recent accomplishments and future directions

Below we summarize some recent highlights of research accomplished using piston core materials and some interesting questions for future study. These examples do not cover all of the exciting work being done. However, they illustrate both the high impact of contemporary studies based on material from piston cores and the prospects for continued high-impact, societally relevant, science in the future.

How does Earth's climate change in response to external forcing?

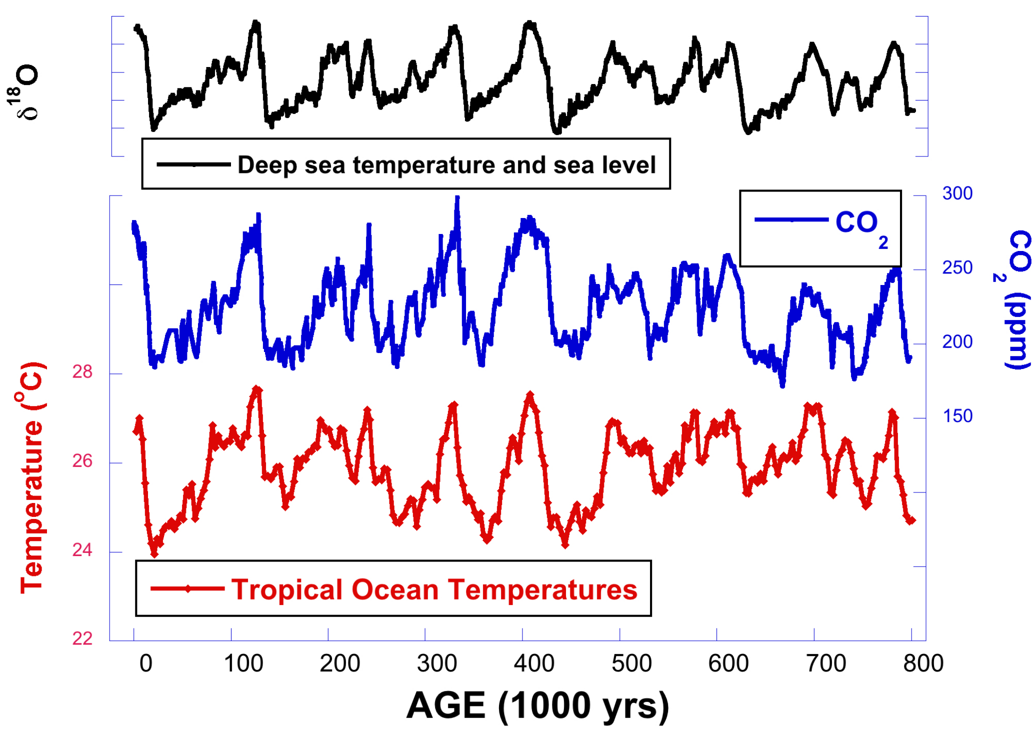

Figure 2. Global ice volume and deep water temperature (top) [*Lisiecki and Raymo*, 2005] and tropical ocean temperature (bottom) [*Herbert et al.*, 2010] are reconstructed from deep sea sediments. Comparison with atmospheric CO_2 reconstructed from ice cores (middle) [*Augustin et al.*, 2004; *Luthi et al.*, 2008] suggests that atmospheric CO_2, global temperature, and global sea level changes are closely linked.

One of the goals of paleoclimate research is to understand how the climate system responds to external forcing (e.g. changes in the distribution of solar insolation due to changes in the Earth's orbit or naturally occurring changes in atmospheric CO_2 concentrations). One aspect of this response is the climate sensitivity (the equilibrium temperature change in response to a given change in radiative forcing). By comparing surface temperature changes to the long Antarctic ice core record of atmospheric CO_2 concentrations, paleoclimate data can help to constrain the warming effect of additional atmospheric CO_2. Sea surface temperature records from long marine sediment cores have provided the best resolved records of surface temperature spanning the length of the ice core CO_2 record (*Figure 2*).

While the equilibrium response of planetary temperature to radiative forcing is a key metric for the validation of climate models, other aspects of the response of the Earth's climate may be equally or even more relevant to how we experience climate change. One important aspect is the spatial structure of the equilibrium temperature response and the related changes in atmospheric circulation and precipitation patterns. Another key question is how inter-annual to centennial scale variability in climate responds to changes in radiative forcing. Both of these aspects of climate response challenge the current generation of ocean-atmosphere models, leaving an important role for the interpretation of paleoclimate data that bears on these questions.

Much progress has been made in understanding the overall spatial structure of temperature changes over the last glacial cycle. Inter-hemispheric temperature differences are correlated to changes in the Atlantic overturning circulation. These inter-hemispheric differences in temperature are associated with latitudinal shifts in the tropical rainfall associated with the Intertropical Convergence Zone. Less well-established are the spatial patterns of the millennial scale abrupt climate changes of the last glacial period. The continued collections of long cores from a variety of high sedimentation rate locations around the globe will allow us to resolve the spatial footprint of these climate changes and better establish the root causes and global linkages of the abrupt climate change events. Reconstructing global temperature for past warm intervals of the late Neogene such the last interglaciation (115-130 ka); the mid-Brunhes, (~400 ka), the mid-Pleistocene (~1.3ma) and the preglacial Pliocene (6-3ma) would provide a better understanding of the role of spatial and temporal insolation changes associated with Earth's orbit. However, accessing these older time periods would require a global distribution of long cores from locations with appropriate sedimentation rates, and targeting locations where Neogene sediment is within meters of the seafloor.

Climate variability on time scales of decades to centuries (e.g. Pacific Decadal Oscillation, Atlantic multidecadal oscillation) is, at present, poorly understood. The historical temperature record suggests that climate variability on these time scales may substantially modulate the global warming signal in response to changes in anthropogenic forcing, creating periods of accelerated warming and periods where warming may slow or even temporarily reverse. Insight into the modes and sensitivity of these multidecadal systems to perturbation is currently limited by the length of the instrumental record. It is critical therefore to document and understand climate changes in the past at a resolution that captures multidecadal variability. This will require sediment records using long cores from a number of very high sedimentation rate locations such as along continental slopes. Longer cores will not only provide longer time series in order to more fully characterize this variability, but will help to establish if the characteristics of this variability (magnitude, frequency) are constant with time, or change in response to changes in background climate state.

The behavior and predictability of the dominant global mode of interannual variability, El Niño-Southern Oscillation (ENSO), under future warming scenarios also remains highly uncertain. At the most basic level, it is not well understand whether ENSO is strongly forced by climatic boundary conditions or weakly forced and thus mostly stochastic in its behavior. However, some progress has been made towards understanding inter-annual

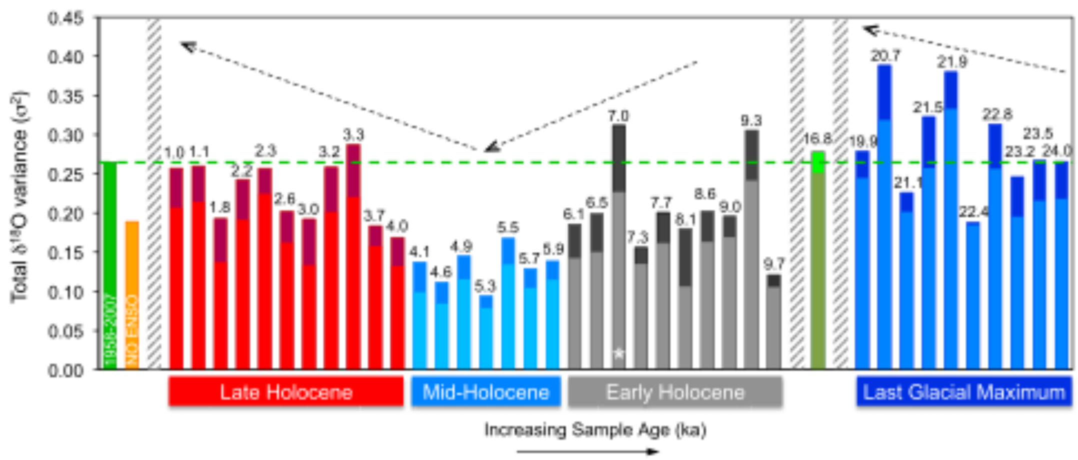

Figure 3. Changes in ocean variability during the Holocene reconstructed from oxygen istotope analyses of individual foraminifera from piston core V21-30. Lower variance in the middle Holocene reflects a reduction in ENSO amplitude and/or frequency, possibly driven by changes in solar insolation [*Koutavas and Joanides*, 2012].

variability, both through reconstructions from annually resolved archives such as coral, and through looking at variability of ocean temperatures from individual foraminifera. Recent studies have used the distribution of individual foraminifera geochemistry values from discrete samples of deep-sea sediment cores to investigate ENSO behavior under different boundary conditions. These studies suggest that ENSO responds to solar precession and glacial-interglacial climate (CO_2 and ice volume) and thus may be strongly forced by boundary conditions. These findings indicate that changing behavior of ENSO from global warming may be predictable and should be a priority target for improving climate model simulations. Future work is needed to document the evolution of different flavors of ENSO (central Pacific, eastern Pacific) and the predictability of ENSO behavior under different climate states. Cores with high sedimentation rates are essential to extend the existing studies.

How do changes in ocean circulation and biogeochemistry affect atmospheric CO_2 concentrations?

The striking similarity of greenhouse gas levels in polar ice cores to marine records over the past 800,000 years provided a key piece of evidence in the continuing puzzle of explaining the amplitude and global extent of ice age climate cycles. It is now clear that during glacial periods, more carbon was sequestered in the subsurface ocean, leading to lower surface ocean and atmospheric CO_2 concentrations. These changes in CO_2 and other greenhouse gases (including the water vapor feedback implied by ocean SST changes) provide much, and perhaps most, of the amplification underlying ice age cycles. Marine sediment proxy evidence has been building support for the now dominant paradigm that the sequestration of carbon in the deep ocean, and thus atmospheric CO_2 changes on orbital time scales, are driven by ocean circulation, biology and sea-ice changes in the Southern Ocean (*Figure 4*).

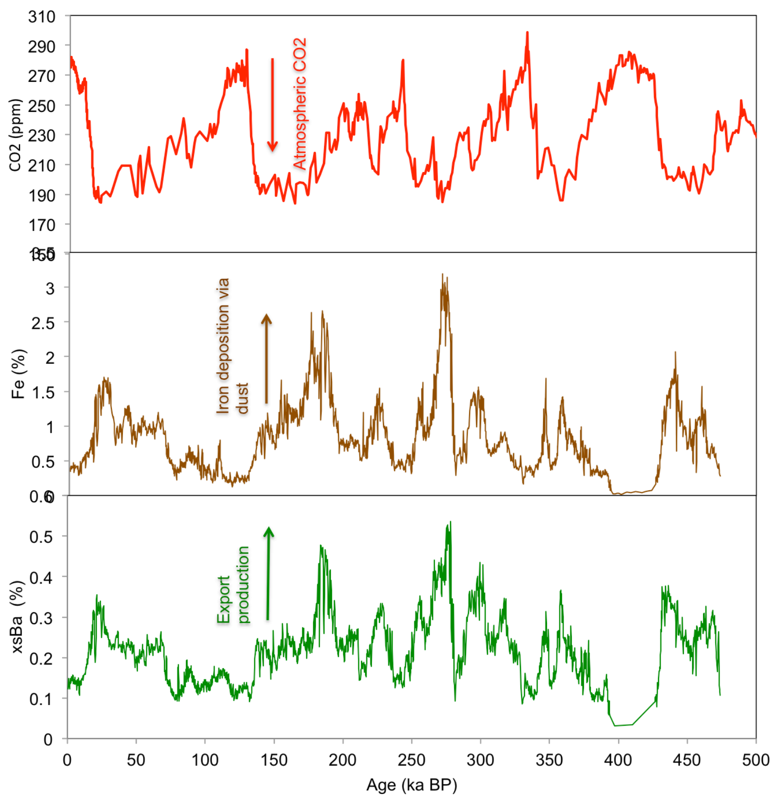

Figure 4. Glacial-Interglacial cycles in atmospheric CO_2 (top) [*Luthi et al*., 2008] are thought to be linked to changes in Southern Ocean biological productivity (bottom) driven, in part, by changes in delivery of the micro-nutrient Fe via dust (middle). Iron and productivity records are from the piston core PS75/59-2 and reported in *Lamy et al*. [2014].

However, key aspects of this hypothesis remain to be tested. How efficiently the deep ocean sequesters atmospheric carbon will depend on the conditions in the surface ocean at the last point of full carbon exchange and equilibration with the atmosphere. An efficient oceanic carbon pump requires that the biological utilization of nutrients and carbon in deepwater formation regions be close to complete. This is the case in the North Atlantic today, but it is thought that North Atlantic Deep Water was less dominant in the glacial ocean. So hypotheses have focused on processes that could make the Southern Ocean loop more efficient. However, these hypotheses, while all centered on the Southern Ocean, differ markedly in the mechanisms, and predictions about the strength and properties of the deep waters emanating from the Southern Ocean.

Changes in Atlantic Ocean circulation over the last glacial cycle are now much better understood as a result of studies using a broad set of tracers, and reconstructions of tracer information at high vertical resolution using transects of sediment cores. As shown in

Figure 5, the benthic foraminiferal $\delta^{18}O$ (related to seawater $\delta^{18}O$ and temperature) during the Last Glacial Maximum shows a larger increase in waters below 1.7 km than above this depth in the South Atlantic. This study emphasized the use of conservative tracers to estimate the ratio of transport to mixing in the deep ocean, and the surprising result is that there was probably increased stratification during the Last Glacial Maximum. This type of study can be extended to non-conservative tracers to measure the amount of carbon stored in the deep-sea and to understand the role of alkalinity changes in past climates. Depth organized tracer information should be extended to other ocean basins and will help to understand the evolution of ocean circulation over time. Not only will these reconstructions allow us to better understand the glacial-interglacial carbon cycle, but will allow paleoclimate researchers to address questions that concern modern oceanographers, such as what sets the ocean circulation in the first place. Since sedimentation rates are often higher along the ocean margins at intermediate water depths, long cores are necessary even to penetrate to the Last Glacial Maximum in many cases. While this approach will require the ability to collect large numbers of piston cores in continental margin locations, the information will allow for quantitative analysis of past ocean circulation in a way that a time series from a single core cannot.

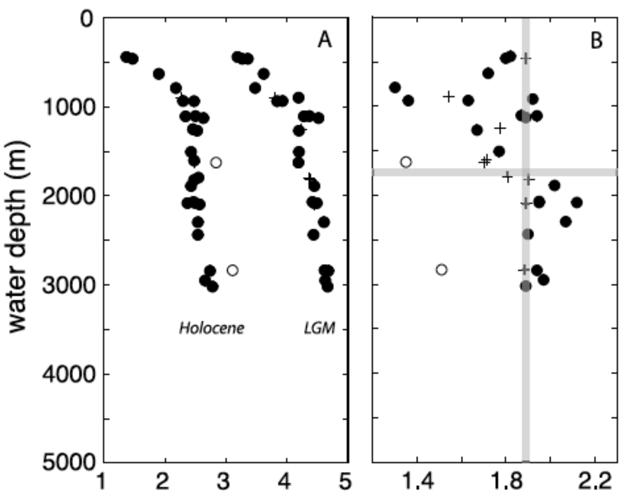

Figure 5. Brazil Margin $\delta^{18}O$ measured on benthic foraminifera from core tops and Last Glacial Maximum (LGM) time slices (left) [*Lund et al*., 2011]. The LGM-Modern difference is shown in the right hand panel. These data show the different structure of the LGM deep Atlantic supporting a 2-cell circulation that is much more separated than in the modern ocean

Perhaps the most direct way to reconstruct the properties of the deep ocean in the past is to analyze the pore fluids deep within the sediment column that, due to the long time scale of diffusion, can still bear a strong imprint of glacial conditions. Collection of long cores for their pore water $\delta^{18}O$ and chloride concentration can provide past constraints on LGM salinity, $\delta^{18}O_{water}$, and with benthic $\delta^{18}O$ data, temperature. With a globally distributed set of data it would be possible to map the temperature and salinity of the LGM ocean, providing an invaluable data set to understand past climate and creating the first realization of the ocean's density structure under boundary conditions different from today. At present such information only exists at a small number of locations worldwide. It is also possible to extract information about LGM deep ocean nutrients, such as preformed nitrate concentrations from pore fluids, which would provide strong constraints on the mechanisms for the lower glacial atmospheric CO_2 concentrations. Reconstructing LGM ocean properties from pore fluids is ideally performed with high-resolution measurements (every 1-3 meters) over ~100 meters of sediment depth which requires ocean drilling, although some information is preserved in the shallower sediment sections sampled by long piston coring. For broad spatial coverage at reasonable cost it may be effective to combine traditional ocean drilling with seafloor drilling vehicles and long piston coring.

How do ice sheets and ice shelves interact with the ocean and climate?

The dynamic behavior of ice sheets, ice caps and glaciers and their relationship to global climate change have become a major concern because of the pronounced influence of ice on regional climate, glacio-fluvial runoff, ocean circulation and sea level. At present, glaciers and ice sheets are experiencing increased ice discharge and accelerating rates of retreat that are likely climate driven. Understanding the inter-relationships between dynamic glacial behavior, particularly tide-water glaciers, oceanic/sedimentary buffering, climate forcing and ocean warming can provide an essential context for the large spatial-scale changes observed over the past century and help us to understand the processes that are likely to control glacier melt in the coming century.

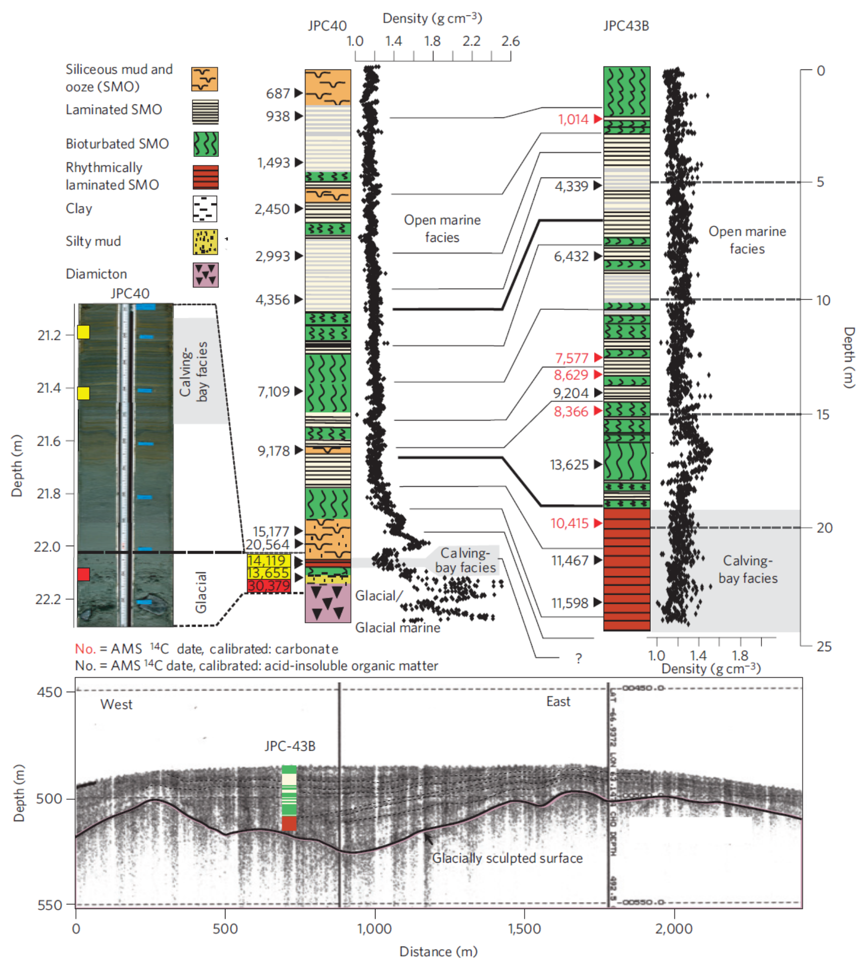

Figure 6. Piston core stratigraphy with a chirp sonar profile from glacial sediments near the East Antarctic Ice Sheet [*Mackintosh et al.*, 2011].

Reconstruction of the rate of change of major ice sheets can only be resolved by sediment cores in high deposition rate areas while an assessment of the extent of ice sheet change requires cores collected over appropriate spatial scales. Due to the extremely high sediment input from ice sheet and glacier margins to adjacent ocean regions, longer coring techniques are necessary to even evaluate decadal scale and longer variability in ocean-ice sheet interactions. Longer sediment core records proximal to tidewater glaciers can provide insight to the ocean-ice-sediment interactions that increasingly appear to govern the complex behavior of ice mass retreat. This is of broad interest because it contributes substantially to the challenge of predicting future global sea-level rise. Recent seismic records in fjords reveal nearly horizontal depositional packages, resulting from decadal-scale retreat of the ice front, yet interpretation of these records is hindered by the extremely high accumulation rates that demand long coring (e.g., off Columbia Glacier, AK). Work involving detailed surveying and piston coring in order to establish the timing of ice sheet retreat has helped to establish that the majority of ice loss from the East Antarctic Ice Sheet during the last glacial termination was driven by ocean warming rather than sea level rise (*Figure 6*). More recently, Weber and colleagues used 33 m and 58 m-long piston cores to construct a highly detailed history of iceberg activity over the deglaciation in the Scotia Sea, which provides a spatially integrated signal from different parts of the Antarctic ice sheet. As the Greenland and Antarctic ice sheets continue melting, it is essential to understand how freshwater influences ocean circulation and drives abrupt changes in climate. Longer sedimentary records can also be used to trace the complex ocean circulation patterns that result from meltwater and icebergs discharge from melting ice sheets, using stable isotopic and ice-rafted debris proxies.

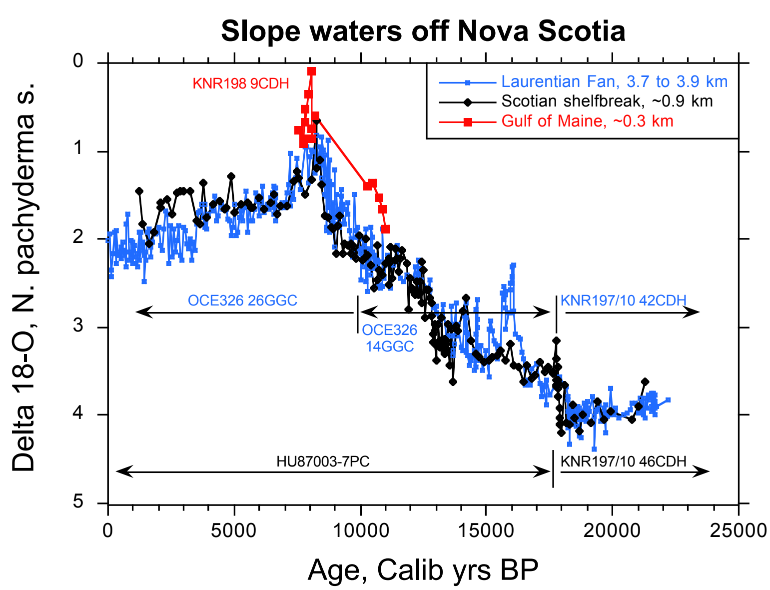

Figure 7. Oxygen isotope ($\delta^{18}O$) in a near surface dwelling foraminifera from the Gulf of Maine, the upper slope south of Sable Island (N.S.), and the Laurentian Fan [*Keigwin et al*., 2005]. At these locations the WHOI long-coring system was deployed to obtain a complete record (Jordan Basin, Gulf of Maine), or to extend existing records that failed to reach the LGM because of high deposition rates[*Keigwin and Pilskaln*, 2015]. These results show that the flood waters at 8.2 ka were concentrated on the continental shelf, as predicted by theory and models.

Study of nearshore, high-deposition rate locations can also reveal how glacial meltwater affects the climate system. The most recent geological-scale meltwater pulse was about 8.2 ka and probably resulted from a sudden collapse of a small ice dome that was blocking Hudson Strait. This event is thought to have resulted in widespread cooling and other climate effects related to a reduction of the North Atlantic's meridional overturning circulation (MOC) due to the injection of meltwater. Paleochemical evidence exists for this process, yet it has been difficult to find the evidence for lowered surface ocean salinity as expressed by low planktonic foraminiferal $\delta^{18}O$. Low $\delta^{18}O$ has been reported from a few locations in the slope water system between Cape Hatteras and the Tail of the Grand Bank, but theory and modeling show that the signal should be strongest on the continental shelf where fresh water stays trapped. New low $\delta^{18}O$ evidence for this process at 8.2 ka has recently been found in the Gulf of Maine, and on the upper slope off Nova Scotia (*Figure 7*). Note the decreasing $\delta^{18}O$ with decreasing distance from shore (and depth), a signal that is likely to reflect lowered salinity, not higher temperature. The Gulf of Maine signal result was found at 19.4 m in a 28 m core collected using the WHOI long-coring system, and illustrates the importance of long-coring on continental shelves and other high deposition rate locations.

How often do geohazards such as tsunami-generating submarine landslides and earthquakes occur?

Recent large magnitude subduction zone earthquakes and consequent tsunamis have brought into sharp focus the need to understand these potential geohazards. Determining the age of the most recent earthquake and the recurrence interval of earthquakes along fault systems is needed to generate probabilistic earthquake hazard maps. While the geophysics community has developed state-of-the-art instruments and technologies to investigate the structure of these subduction zones at an unprecedented scale, sediment cores are needed to infer the timing of deformation. There are two ways in which long sediment cores can provide information on earthquake recurrence. The first approach is to use the geophysical information to identify the fault structures, and to core through to the interval containing the fault displacement. The timing of past fault movements can then be determined by standard methods developed for paleoclimate studies. In this approach, sediment cores need to be long enough to reach the fault. The second approach is to identify and date distal turbidite deposits that were triggered by subduction zone earthquakes. In this approach, a number of cores need to be collected over a relatively large area in order to determine which of the turbidite deposits are regionally coherent and thus likely to have been triggered by earthquakes. The length of the cores determines the timescale over which earthquake events are catalogued and thus the confidence in the average recurrence interval and its variability. This type of study provides important information for assessing seismic hazards in regions such as the Pacific Northwest where large, long recurrence interval events may affect major population centers.

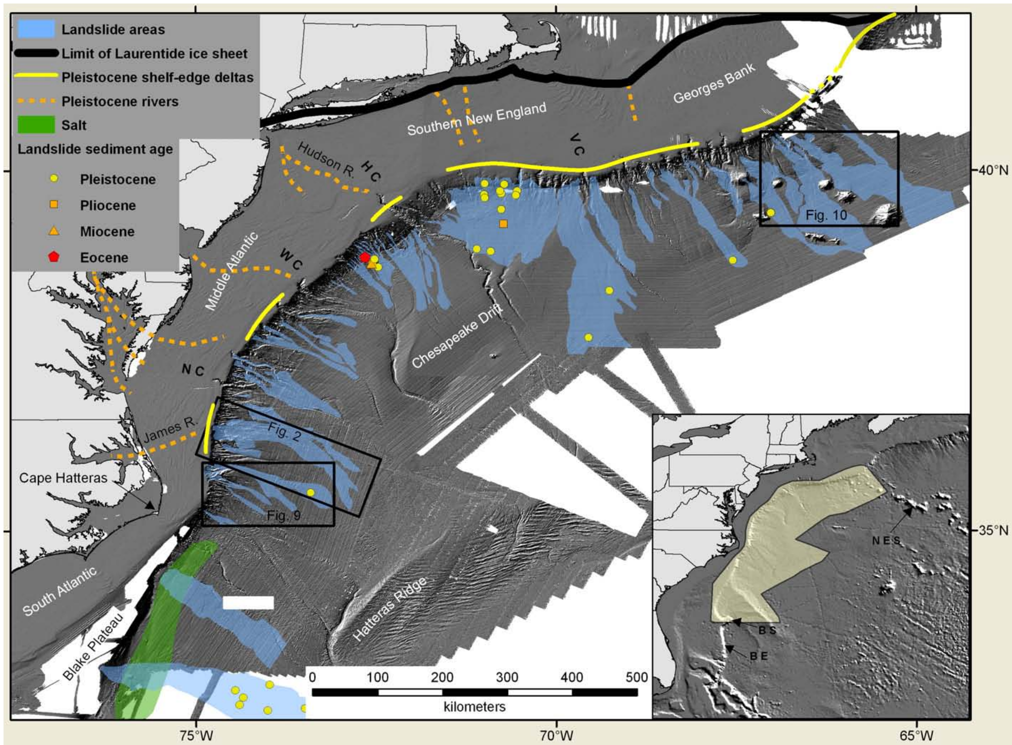

Figure 8. Regional morphology and submarine landslide distribution along the U.S. Atlantic Margin [*Twichell et al*., 2009].

Submarine landslides also constitute a geohazard given that they might trigger a tsunami that poses a danger to large coastal population centers along continental margins. From a societal perspective, these events, although rare, can be economically devastating and lead to huge loss of life. New evidence of numerous, active seafloor seeps along the slope of the U.S. Atlantic margin, many of which are associated with regionally extensive submarine landslides, highlight the fundamental importance of fluid flow and gas migration in stability and evolution of the margin *(Figure 8)*. Long cores collected from large landslides such as the Currituck and Cape Fear Slides, as well as intact regions along the margin with extensive hydrate accumulations or active seafloor seepage, will be critical in developing age models for slope failure recurrence intervals, the prediction of seafloor stability through geotechnical analyses, and stratigraphic reconstructions to identify weak layers and fluid flow pathways that may be acting as slip planes for incipient failures. Work in this realm also relates to scientific objectives concerning tectonic reconstructions, from crustal evolution to sedimentary processes that govern the evolution of the margin; subseafloor fluid flow and chemical fluxes; and climate fluctuation and ocean circulation interactions that potentially contribute to slope instability through hydrate dissociation.

How does mid-ocean ridge volcanism change with time?

There is tantalizing evidence that mid-ocean ridge volcanism and the creation of new oceanic crust may vary due to changing sea-level and other factors. Long sediment cores collected on the flanks of mid-ocean ridges are necessary to investigate this variability and understand its causes.

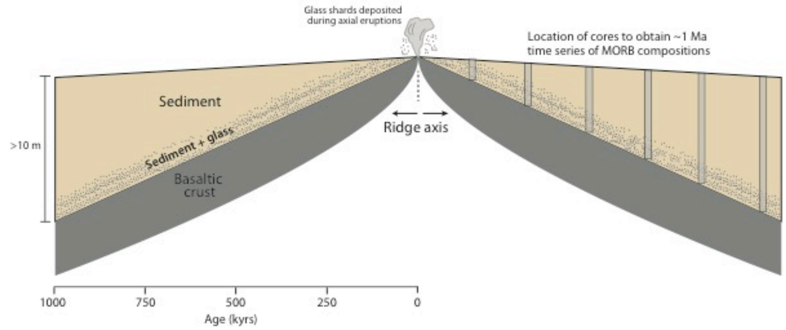

Figure 9. Schematic illustrating how a series of sediment cores from the mid-ocean ridge can be combined to obtain a history of ridge volcanism recorded in the volcanic glass shards that accumulate in the sediment near the ridge.

It has been known for decades that sediment cores collected near the mid-ocean ridge might occasionally encounter basement and recover a chunk of basalt. More recent work has revealed that the sediments at the bottom of such cores also record up to a 50,000 year time series of information through glass shards that are ejected into the water column, carried by currents and retained in the sediment. With twenty carefully placed cores at increasing distance from the ridge axis, one could then obtain a continuous 1 million year long record of ridge volcanism (*Figure 9*). Previous attempts to examine changes in ridge volcanism from the dredging fault scarps have been limited by spotty spatial coverage, uncertain age, and the collection of rock samples that are highly altered through long exposure to seawater. In contrast, the basement samples at the bottom of the sediment cores are remarkably fresh—they have been isolated from seawater interaction and the glass shards are pristine. Furthermore, ages can be constrained by the age of the crust and all the age tools that have been developed to date sediment cores for paleo-

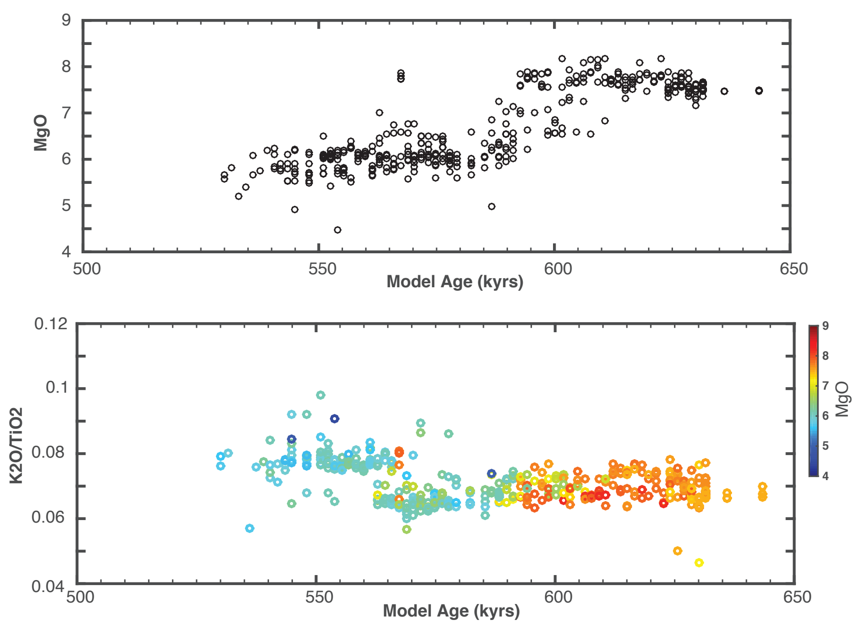

Figure 10. Chemical measurements from glass shards from a piston core near the Juan de Fuca Ridge showing that magma source composition (K_2O/TiO_2) and magma temperature (MgO) change at different times. [*Langmuir*, upublished data]

environmental reconstruction. This opens up numerous lines of investigation of ocean ridge volcanism that were not previously possible without accurate dating.

Langmuir and colleagues started the first application of this approach with the collection of piston cores off the Juan de Fuca Ridge in September of 2014, with the aim to investigate if hydrothermal activity might vary with sea level changes caused by glacial cycles. Preliminary data show that in addition to reconstructing changes in ridge activity, the compositions of magmas can be reconstructed as well (*Figure 10*) suggesting changes in magma composition at a glacial/interglacial transition. Intriguingly, the changes in magma composition and magma temperature happen at different times.

For a full characterization of ridge volcanism, more locations around the world would need to be investigated, with 20-40 piston cores of 20 m length at each location to get a 1-2 Ma time series. If this were done at 20 or so locations around the world in the next decade or two, it would require as many as 800 new piston cores. Coring in marine sediments near subaerial volcanoes may also allow for long continuous time-series from these systems, and address the more general question of the progressive evolution of volcanic systems. We anticipate significant demand for piston cores to meet the demands of this emerging field.

What is the extent of the subseafloor biosphere and how does it function?

Piston coring expeditions using the WHOI Long-coring System have provided the material necessary to revolutionize understanding of subseafloor sedimentary life, particularly in subtropical gyres. These cores have enabled quantification of Earth's subseafloor biomass and its global distribution (*Figure 11*), demonstrated that aerobic respiration can persist in subseafloor sediment for tens of millions of years (*Figure 12*), and provide strong evidence that oxygen and aerobic communities persist throughout the sediment, from seafloor to basement, in much of the world ocean.

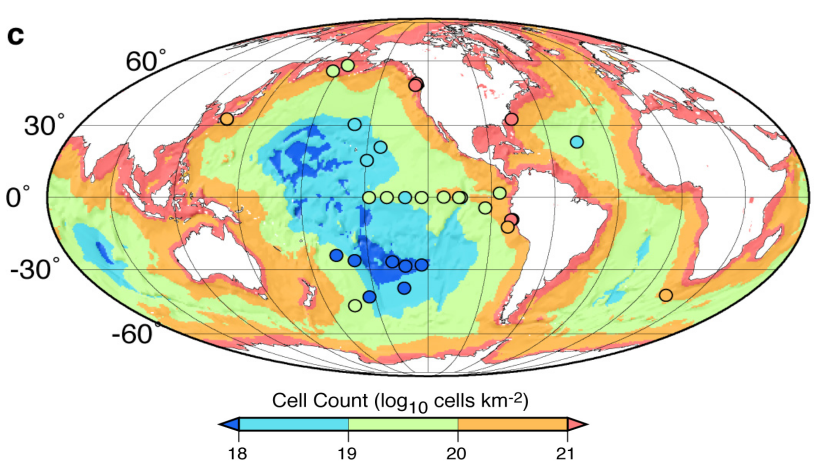

Figure 11. Global distribution of marine sedimentary cell abundance [*Kallmeyer et al*., 2012]. Distribution derived from integrated number of cells at representative sites (colored dots) and sediment thickness. Dot colors indicate numbers of cells calculated for actual sites ($\log_{10}$ cells/km^2). Data for all of the South Pacific gyre sites, the North Pacific gyre sites, and most of the equatorial Pacific sites are from piston cores obtained with the WHOI Long-coring system. The remaining sites are from ODP/IODP drill cores.

Despite these advances, the subseafloor biosphere is one of Earth's least explored biomes. Although microbes are approximately as abundant in marine sediment as in the ocean, current models rarely account for their possible impact on global biogeochemical cycling. Energy fluxes are so low in subseafloor sediment that the nature of microbial evolution and diversity may be fundamentally different than in the surface world. However, we lack fundamental knowledge of microbial community composition, diversity and metabolism in deep subseafloor environments. Furthermore, the limits of subseafloor sedimentary life are not yet known in terms of any environmental properties, including depth, temperature, energy availability, or geologic age. In short, the little-known deep biosphere is well poised for breakthrough discoveries through UNOLS piston coring over the full range of ocean water depths.

Piston coring of sediment in deep trenches provides one example of the extraordinary new advances that can be made by future UNOLS coring over the full range of ocean depths (0 to 11 km below sea level). Such coring will provide an extraordinary opportunity to (i) test the "island biogeography" of subseafloor sedimentary communities in the deepest regions of the world ocean, (ii) identify the evolutionary adaptations of subseafloor anaerobes to the highest pressure regimes that can be readily sampled in the natural world, and (iii) document the relationship of subseafloor microbes in the deep trenches to microbes in the overlying hadal (≥6 kmbsl) ocean. The deep subseafloor communities of the major trenches have never been sampled, and likely possess unique organisms and physiologies. The biogeography of subseafloor sedimentary communities in deep trenches is unknown. Do all trenches contain the same community or has each trench evolved separately? How do these communities and their capabilities change over the full range of subseafloor redox zones (from the near-seafloor O_2 reduction zone to the deep sulfate-reduction zone and deeper methanogenic zone)? The rates and relative importance of all major biological processes, including carbon fixation and remineralization, are also essentially unknown in subseafloor sediment of the hadal ocean. Finally, the physiological adaptations that allow subseafloor anaerobes to thrive in this very high-pressure realm are also unknown.

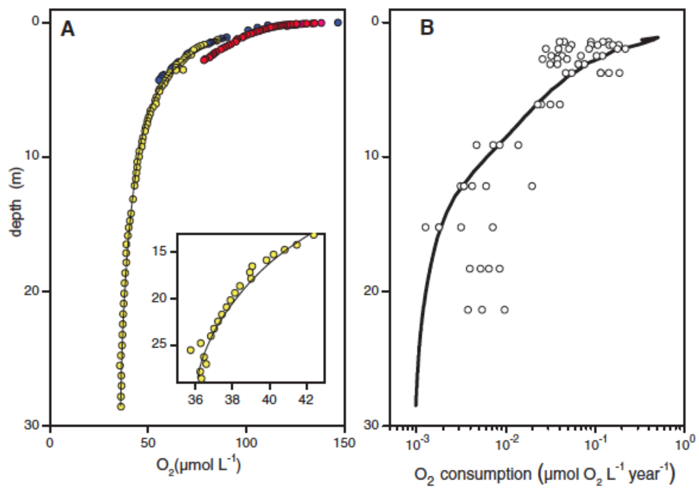

Figure 12. Dissolved O_2 penetration (A) and aerobic respiration (B) deep beneath the seafloor of the North Pacific gyre [*Roy et al.*, 2012]. This study was the first to demonstrate that (i) O_2 penetrates tens of meters beneath the seafloor, and (ii) aerobic respiration persists in gyre sediment for many tens of million

Priorities of the Decadal Survey of Ocean Science (DSOS)

Continued access to capable and reliable sediment coring systems is essential to address almost all of the priority research questions identified by the DSOS (*Figure 13*). Piston coring capability is necessary to understand the processes controlling the rates and mechanisms of ice sheet decay by providing a detailed history of these processes over the last glacial cycle (Question 1). Sediments accumulate rapidly in near shore environments, and long piston cores from estuarine and near shore environments could provide a detailed record of physical and ecosystem processes over the historical period and throughout the Holocene (Question 2). The link between ocean circulation, biogeochemistry and climate has been a primary focus of paleoceanographic studies using piston cores, and such studies will likely continue to enhance our understanding of these links (Question 3). Microfossils in deep-sea sediments can provide robust data sets for studies in evolutionary biology. While such studies have often focused on major biotic turnovers in Earth history that are generally beyond the reach of piston coring (and in the realm of ocean drilling), material collected from piston cores could be used to investigate the response of biota to more recent environmental changes (Question 4). Ocean sediment cores have been instrumental in understanding the development of ocean basins, and we have outlined above a new project to use piston cores to understand mid-ocean ridge processes (Question 6). Sediment coring can provide information on recurrence intervals for subduction zone earthquakes and undersea landslides that can produce large, destructive tsunamis (Question 7). And, inherently the only way to examine the chemical and biological character of the subseafloor environment is to sample it using sediment coring technologies (Question 8).

Decadal Ocean Survey Priority Questions

1. What are the rates, mechanisms, impacts, and geographic variability of sea level change?
2. How are the coastal and estuarine ocean and their ecosystems influenced by the global hydrologic cycle, land use, and upwelling from the deep ocean?
3. How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?
4. What is the role of biodiversity in the resilience of marine ecosystems and how will it be affected by natural and anthropogenic changes?
5. How different will marine food webs be at mid-century? In the next 100 years?
6. What are the processes that control the formation and evolution of ocean basins?
7. How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?
8. What is the geophysical, chemical, and biological character of the subseafloor environment and how does it affect global elemental cycles and understanding of the origin and evolution of life?

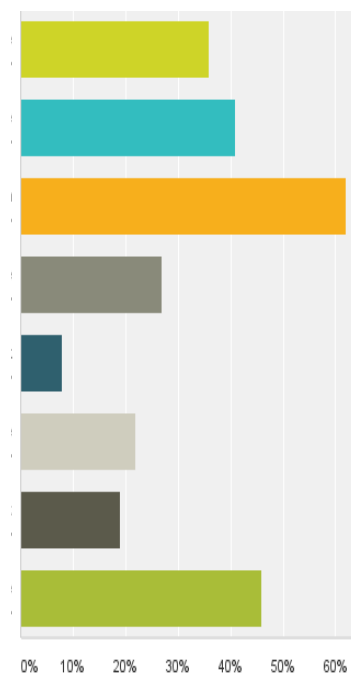

Figure 13. Decadal Ocean Survey priority questions, and the percentage of survey respondents who felt their research using piston cores addressed these questions.

In summary, piston coring during the next decade will play an important role in 7 out of 8 DSOS research priorities. The DSOS report explicitly recognizes the importance to ocean sciences of coring and ships that can provide support for coring, and expresses concern that this capability is retained as the research fleet evolves. These concerns are echoed in this report through the scientific rationale for acquiring new sediment cores and the essential role such cores play in existing and emerging research avenues.

The broader impact of sediment core studies

The ongoing collection of new sediment cores provides a service of lasting value to the entire geoscience community. While core collection is often initiated and carried out by a small group of investigators with the intent to address a specific scientific question, the collection often ends up benefitting a much larger scientific community because samples are available to the community at NSF-funded core repositories. A coring cruise is labor intensive, and for every PI there are usually a number of graduate students who also gain experience and new insights by working at sea.

Of the respondents to our survey who use material from piston cores in their research, only 30% have actually served as a PI on a coring cruise themselves. Most express satisfaction that they have good access to material that is archived. Often, studies on archived core materials are completed decades after the original cores were collected. Thus, collection and curation of new sediment cores renews the incredible legacy provided by the thousands of cores collected over 60 plus years by the U.S. research community.

Our ability to acquire samples from deep drilling of oceanic sediments and crust also rests upon the piston coring capabilities of the U.S. research fleet. A site survey cruise, which includes the collection of piston cores along with detailed geophysical survey data, is a pre-requisite for the deep drilling expeditions coordinated by IODP that provide material to a broad community of Earth Scientists.

Scientific results based on sediment cores resonate with researchers in the broader Geoscience (GEO) and Ocean Sciences (OCE) communities. For example, physical oceanographers have begun modeling the paleoceanographic observation that deep water masses in the North Atlantic were arrayed differently during the Last Glacial Maximum. This finding has spurred much fundamental research into the controls on deep ocean circulation, particularly the Atlantic Meridional Overturning Circulation. There is also a strong synergy between paleoceanographic studies and the long climate records collected by the polar ice coring community (PLR). The reconstructions are well matched in time and resolution, and the records from the different archives are often interpreted together. Perhaps, most critical is the role that paleoclimate data generated from sediment cores have played in our understanding of the Earth's Climate (AGS). These data have been used as a test for the Global Climate Models that are being developed to predict future changes. Compilations of data collected from a sediment cores distributed globally (e.g. CLIMAP and its descendants) have been particularly useful to the modeling community.

Science-Driven Coring Needs

Hierarchy of Coring Systems

Coring systems can be ranked by depth of penetration, complexity, and shipboard requirements. Multi-cores (MC) are easily deployed using the 9/16th " trawl wire, and they give immediate insight into the sediment properties such as texture or color because the tubing is clear. If a MC penetrates and recovers a full ~50 cm, it is a good indication that the site is suitable for longer coring. Multi-cores are essential for capturing undisturbed samples from sediment-water interface for proxy calibration and to extend time series close to the present day.

Sediment properties can also be assessed with a giant gravity core (GGC) that is best launched and recovered vertically using a ¼" hydro wire. This type of corer typically does not exceed 5 m (a standard 20' length of PVC pipe) and is more appropriate if there is any doubt about how soft the bottom is and whether deeper coring is possible. If a priori the seafloor is known to be soft, it is generally a matter of choice as to whether the GGC or MC is done first. Either way, one of these is usually deployed before Jumbo Piston Coring (JPC, typically 6-25 m) is considered. In the absence of good sub-bottom imaging systems such as 3.5 kHz chirp sonar, it is often necessary and prudent to first deploy shorter piston cores before moving on to a longer piston core if the sediment characteristics are not well known in order to remain within the safety limits of the wire and winch during core recovery. For cruises where the objective is piston coring, at most stations a combination of MC, GGC, and JPC is necessary for proxy calibration at the sediment-water interface, and to insure that there are no gaps in recovery between the three tools. Piston coring is part of a site survey cruise and is a pre-requisite to scientific drilling under the auspices of IODP. Piston coring devices such as the WHOI Long-coring System (up to 46 m) have also been typically deployed in previously cored or well-surveyed environments where the sedimentary history and character can be anticipated based on this previously acquired knowledge.

Priorities

Based on community input, historic usage patterns and anticipated needs for the outstanding scientific questions posed above, the workshop participants arrived at a ranked list of priorities for coring infrastructure in the coming decades. The first priority is the ability to deploy short (gravity and multi-core) coring systems from all Global, Ocean and Regional Class vessels. This top priority was driven by the continued high demand from a large and diverse pool of users in the Ocean Science community. The second priority is to upgrade to the Jumbo Piston Coring systems to function reliably in challenging environments. We recommend that this system be portable and capable of deployment on all Global and Ocean Class Vessels to a length of 20 meters. A flexible and robust JPC system, capable of operation in most oceanic and sedimentary environments is expected to remain the workhorse of paleo-environmental studies. The third priority is the capability to deploy a long-coring system, or a hybrid version of it from one of the large research vessels. This will enable some of the cutting edge applications detailed above, such as extending high resolution climate studies to other climate states or the exploration of the subseafloor biosphere. Our final priority is the continued exploration and development of alternative mechanisms for sediment coring and drilling that provide flexible alternatives for science that benefits from the recovery of 100 m or more of sediment.

1. Multi-core and gravity core capability

Multi-cores and gravity cores are portable, easy to use, inexpensive, enable rapid gathering of samples. While the focus of this report is on longer (piston) coring technologies, these shorter coring tools have a very broad user base within the marine geology and biogeochemistry communities. Short coring techniques are important for all oceanographic, ocean engineering, and environmental (monitoring, for example) disciplines. Multi-cores and well-preserved sediment surface samples from gravity cores also provide the link between modern processes and conditions and the historical records gleaned from longer cores. All longer coring types require GGCs or MCs for exploratory characterization and "splicing across seafloor surface boundary." The community needs to have the capacity to collect multi-cores, gravity cores, and a range of other near surface sediment sampling devices all Global, Ocean and Regional class ships. This is a capability that must be maintained, and kept up-to-date.

Ocean/sedimentary environments: Multi-coring and gravity coring capabilities are essential in all environments, from shallow coastal settings to deep sea/trenches, and from the tropics to the poles. These systems need to be capable of deployment at all water depths up to 11,000 m (full ocean depth).

Personnel Requirements: These coring systems are inexpensive to transport, although all ships should have some the infrastructure to utilize these systems. While these systems are intuitive to use, and they may not require special technical support to operate, some training of the shipboard technical staff would be necessary. However, technical expertise must be maintained for training, development and maintenance.

2. Robust and portable jumbo piston coring system

The Jumbo Piston Corer (JPC) was developed in the late 1980s and the first cruise dedicated to using this new tool was in 1990 (*Atlantis II* 125). On that cruise in the Gulf of California, several cores in excess of 19 m were recovered from diverse basins. A few years later along Blake-Bahama Outer Ridges (*Knorr* 140), JPCs as long as 30 m were deployed and maximum recovery was nearly 24 m. The JPC has been the workhorse of the U.S. piston coring community for 25 years, and is likely to continue in this role.

Access to a robust JPC system is critical to enable progress on all of the scientific topics highlighted above. In the online survey, which represented the views of scientists across a variety of disciplines, 89% of respondents had used material from piston cores, and 97% planned to do so in the future. The respondents overwhelmingly (96%) felt that it is important that we have the ability to collect cores exceeding 15 m in length. Many of the survey comments noted that despite valiant efforts, the number of piston cores collected and the length of the collected cores were limited by faulty equipment (winches, cranes), configurations of deck space and equipment that did not allow for the make-up and recovery of full length piston cores, and new safety regulations which limit the amount of tension the trawl wire can experience before being replaced. Here we recommend improvements to the existing JPC systems to ensure routine collection of cores up to 20-25 m on all Global and Ocean Class Research Vessels.

Essential to the success of coring on these vessels is appropriate deck handling equipment and winches. Recovering a JPC has often taxed the limits of the winches and wires, requiring up to 25,000 lbs or more of pull out. This problem has been compounded by several factors in recent years:

1) Jumbo (vs. smaller diameter) piston cores experience more friction as they are pulled from the sediments. However, smaller diameter cores are almost never used any more as the proliferation of types of measurements in paleo-environmental studies has increased the need for higher sediment volumes.
2) Cores are increasingly being collected in less ideal sedimentary environments, such as along the continental margins. Many of the lithologies present offer more resistance to pullout than deep sea oozes.
3) If a steel trawl wire is used, the weight of the wire can become quite significant as cores are collected at deeper water depth (7,000 lb in 5 km of water) and adds to the tension at pull-out.
4) New safety regulations limit the amount of allowed tension on the wire.

While the 9/16" trawl wire was used to deploy and recover piston cores for many years, it is no longer meeting the needs of the 21st century coring community. One possible remedy for this problem is conversion to synthetic rope, which has the advantage of both added strength and neutral buoyancy (no added weight). This will require new winches and modified handling systems. New investment now in synthetic rope may give us future flexibility and allow us to safely reach the deepest parts of the ocean.

The committee is unanimous that new technologies must be adopted as soon as possible to keep the U.S. in the forefront of scientific seafloor coring. While conversion to synthetic rope may be part of the solution, it will also be necessary to come up with configurations for the efficient and reliable deployment and recovery of piston cores on the existing and future global and ocean class research vessels.

In addition to the conventional JPC system, another possibility for recovering cores up to 25 meters in length is a design concept that results in a downsized version of the WHOI Long Corer. If considered, "Long Corer Light" could be deployed from either of the new Ocean Class vessels. As envisioned, this system could be comprised entirely of recycled hardware from the existing Long Corer inventory: barrels, couplings, support system, acoustic release module, extrusion system and more. A new smaller an less complex Grapple would be required to control the large corer during launch and recovery ops, and enable horizontal to vertical and Starboard to Stern transitions of the assembled core.

With this system, cores up to 80' (25m) long could be deployed from the new AGORs. It would be proposed that the "Long Corer Light", like the original Long Corer, would employ high strength fiber ropes.

Ocean/sedimentary environments: Given the breadth of science supported by piston coring outlined above, such a system must be capable of operating not only in homogeneous deep sea oozes, but also in many less than ideal coring environments, on continental margins, near mid-ocean ridges, in heterogeneous sediments, through landslide deposits, in nearshore environments and at full-ocean depth (11 km below sealevel). Such environments create challenges as they have the potential to greatly increase the force necessary to pull the piston core out of the sediments.

Personnel Requirements: The Jumbo piston coring systems require special technical support to operate. Technical expertise must be maintained for training, development and maintenance of these systems. Presently, support for piston coring is provided by the Oregon State University sampling group as a facility that can be requested at the time of proposing a coring cruise. Workshop participants and community comments from the online survey indicated widespread satisfaction with the service provided by the OSU coring group. As envisioned, the 'Long Corer Light" could be operated by OSU in a manner similar to the conventional JPC system.

3. Long-coring system

The WHOI Long-coring System was operated on the R/V *Knorr* until its retirement in 2014. It is a piston-coring system that takes continuous cores with a maximum length of 46.2 m, an outer corer diameter of 4.875" and an inner diameter of 4.375". As presently configured, the system could take cores in up to 7400 meters of water, less than the target capability of 11000 meters below sea level. The coring system can be operated in all major marine environments ranging from coastal to deep ocean (including trenches) except fast ice. Types of sedimentary environments that can be cored include all major marine sediment types, excluding glacial debris, coral rubble and homogeneous sand. With the existing traction winch and drum, and an additional 1500 meters of rope, all depths in the Atlantic (including the Puerto Rico Trench) could be cored. Coring to 46 m at full Pacific Ocean depths (11 km) will require a new drum.

The existing long-coring system was only briefly in use (2007-2014), but the system has collected sediments with relatively little distortion, and has enabled a broad range of science. This includes, but is not limited to, (i) testing hypotheses of LGM water chemistry at water depths greater than 2 to 4 km, (ii) establishing ultra-high-resolution of ocean and climate variability over the past 150 kyr at locations with rapid sediment accumulation, and understanding the underlying forcing mechanisms for climate change on various time scales, and (iii) deep biosphere studies. Examples of future uses could include research into sea level change, earthquake recurrence intervals, etc. from nearshore sediments that accumulate at high deposition rate.

The long-coring system requires a large (Global Class) research vessel. Due to the weight of the system, highly specialized equipment is required to deploy and recover the long-corer. The system was built with a dedicated winch and synthetic rope capable of recovering the corer. Due to the complexity of the deployment and recovery systems, and that special modifications need to be made to accommodate the system, at the time of writing, no UNOLS vessels are capable of handling the Long Core system. We recommend that one ship with global capabilities be configured and strengthened to support the long-coring system.

Personnel Requirements: The long-coring system requires special technical support to operate. Technical expertise must be maintained for development and maintenance of these systems. Presently, support for long-coring is provided by WHOI as a facility that can be requested at the time of proposing a coring cruise.

4. Exploration and development of alternative means for sediment coring and drilling

Long drill-based cores can address key scientific goals that require recovery of sediment from greater sediment depths than can be achieved with standard piston coring. For example, precise reconstruction of Last Glacial Maximum temperature and salinity from pore water chemistry requires data collection to at least the inflection point where the values most representative of glacial conditions are located. In many cases this is beyond the 40 m depth of penetration of our longest piston coring system. In addition, such reconstruction is improved by sampling the pore water gradient well below the inflection point, such that 100 m cores are desirable.

Deeper sampling will also be important in study of the deep biosphere and many other topics. Truly high-resolution sampling of climate at different boundary conditions and past warm climate intervals generally can be sampled with seafloor drilling. Drilling enables the penetration and recovery of hard grounds including drowned coral reefs for studies of past sea level and annually resolved records of climate change. Drilling also allows the sampling of glacial diamictites at ice margins, improving our understanding of large ice sheet dynamics.

Tectonic and geophysical processes can also be studied with long drill-based cores. For example, earthquake recurrence intervals can be measured over long time spans for near shore regions affected by tectonics, and very long records of paleoclimate and volcanism can be developed from the same cores to understand the link between the two. Borehole measurements can be made in real time, and fluid transport and hydrostatic pressures can be measured by "corking" the hole both at spreading centers and subduction zones. Subduction zones themselves are an exciting new frontier in studying the global balance of seawater chemistry. Indeed, this technology may allow new interdisciplinary studies where the biosphere, geochemistry, and tectonics are all linked in the same project.

Ocean drilling has been the only option for collecting sediment cores longer than 50 m. However, deep-sea drilling is now handled through the International Ocean Drilling Program. Sea-floor based drilling and coring systems can also be requested through

IODP as a mission specific platform. However, projects proposed through IODP typically take many years from inception to execution, and the IODP structure is not ideally suited to small groups of investigators or projects with limited goals. As these seafloor based systems continue to develop, we should explore various models of operating these systems in order to maximize progress in the important scientific areas that require deep penetration into the seafloor.

Here we suggest that scientific progress on many questions that are poorly suited to the IODP structure could be maximized by leasing ship time and/or equipment. If time on the R/V JOIDES Resolution or other drill ships can be leased for a reasonable cost to NSF this may provide a good solution for project-specific drilling expeditions that require flexibility outside of the IODP structure.

Another possibility is exploring the use of sea-floor based remotely operated platforms for drilling and coring. While most deep-sea drilling is done from the rig floor of dedicated drill ships, some systems have moved the drill rig from the ship to the seafloor itself. These platforms are similar to ROVs in that they put data, power, imaging, a manipulator arm, and a long corer on the sediment surface. Operated from the ship via telemetry, over 100 meters of undisturbed core can be recovered and the system provides a very stable platform in shallow water settings where heave might otherwise limit ship based coring. Examples of these tools include the MARUM-MeBo operated by the group at Bremen (80 or 200 meters of core) and the Sea Floor Drills (SFD) operated by the US based company Seafloor Geotec (100 meter cores). Because of its handling system, the SFD can be deployed in all ocean environments where ROVs are traditionally used. The main limitations of these systems are the large deck space required, and the need for a large displacement vessel.

Several categories of coring science are enabled by this technology. In general, for the same time interval of the past, jumping from 20 to 150 m allows for drilling of greatly expanded sections. These will be important in study of the deep biosphere and many other topics. Truly high-resolution sampling of climate at different boundary conditions and past warm climate intervals generally can be sampled with seafloor drilling. Being able to penetrate and recover hard grounds also enables the drilling of drowned coral reefs for studies of past sea level and annually resolved records of climate change. It also allows the drilling of glacial diamictites at ice margins, improving our understanding of large ice sheet dynamics. Because the platform is stable at the seafloor all of these science goals will benefit from enhanced core recovery and deeper penetration.

Maximizing Impact of Coring Infrastructure

Importance of expertise, material condition, and development of coring systems

As with any equipment that is used at sea, coring equipment must be maintained and new developments must be pursued. Presently, much of this effort is led by the OSU coring team as a service of NSF Facilities, so that any principal investigator can lead a coring cruise, regardless of previous coring experience. In addition, we must be careful to nurture individual efforts, such as that which led to the Long-coring System at WHOI. We must keep the Coring Facilities business model because it makes it easy to go coring, but nevertheless our seagoing community is small compared to the number of users of core sediment. It is important to the future of marine geology that we continue to add new members to the coring community. This can be done through better advertising of upcoming cruises, and through recruitment of students, postdocs, and junior faculty. It is not necessary to have piston-coring "training cruises," but having a few members of the next generation aboard each already funded coring cruise will go a long way to keeping core-based lines of research active in the future. Emphasis on these goals in future coring proposals and cruises will ensure a well-trained and diverse group of "coring-capable" PIs in the future.

There is also a need to increase community involvement and coordination in coring expeditions. This will help develop coring expertise in the next generation of researchers, but in addition would make more effective use of facilities such as the long-coring system. For example, if several PIs each had a few especially promising target locations for long-coring in the same general ocean region, then it would be cost effective to organize and advertise the possibility of a community cruise to use a device such as the long coring system. That way, a single principal investigator who could meet 90 % of his or her coring needs with the JPC (e.g in developing a depth transect), but who would benefit from one much longer "type section" to give a longer temporal perspective would be able to obtain this core without justifying an entire long-coring expedition. This is how the French operated R/V *Marion-Dufresne* to accomplish IMAGES coring with their long-coring system. Coordination of such a program could take several forms, such as regular meetings (or virtual meetings) that bring researchers together around specific geographic regions. Long-term planning at this level, including regional foci, would foster such planning and interactions.

While most of this document has focused on the exciting new science that can be carried out at new locations in the ocean, it is also necessary to collect fresh core material from sites where cores have been collected. As noted earlier, there are many more consumers of core sediment than there are leaders of coring expeditions. New analytical methods and new hypotheses continue to be developed, while existing core collections become depleted. Some cores are heavily sampled and no longer useful for some studies. Others were collected and stored using methods that render them inappropriate for some types of analyses. The community needs to be open to the idea that if cores are so oversampled as to be useless then it is time to get new cores.

Importance of cutting edge surveying equipment and expertise

Collecting the best sediment cores for specific scientific needs requires high quality imaging of the seafloor and sub-seafloor sediments. Seeing into the seafloor helps in (1) coring the best location; (2) rigging the core for the expected environment so as to minimize bent pipe, loss of corer and wire, etc.; (3) providing a regional context for the core site; (4) fulfilling site survey requirements for ocean drilling.

Shipboard surveys fall into two categories: seafloor imaging (mapping) and the subseafloor imaging (profiling). It is critical that survey technologies such as multibeam mapping systems and 3.5 kHz chirp profiling are on the research vessels that will be used for piston coring cruises, are in good working order, and the technical expertise is onboard to maintain and troubleshoot the systems. If working properly, the 3.5 kHz and CHIRP systems yield submeter resolution with penetration based on sediment type; 20 – 30 meters of penetration in sandy sediment that systematically increases with clay content with maximum depths of penetration on the order of 70 meters. For deeper coring or drilling, deeper imaging may be required; this usually involves installation of a single or multichannel seismic system on the research vessel, or use of a dedicated seismic vessel.

The coupling of multi-beam mapping systems to GPS-based navigation and dynamic positioning systems has revolutionized our ability to target collection of sediment cores in locations that would have been deemed unsuitable for coring in the past. For example, small areas of deposition on areas of elevated bathymetry in heavily eroded terrain can enable paleoenvironmental studies in these locations. These imaging systems are also critical to many of the more novel applications of coring outlined above—for example (i) finding the locations on the Mid-Ocean Ridge that would provide sediments of suitable thickness to recover glass shards near the contact with basement, or (ii) coring a fault surface to date recent seismic activity.

The support and development of these technologies and emerging surveying technologies is critical for enabling science-driven coring and for maintaining a leadership position in science based on marine sediment coring.

Potential for International Collaboration

International collaborations have often been fruitful and should be encouraged where appropriate. For example, international coordination through the IODP and its predecessors has been key to providing U.S. researches access to deep-sea drilling material. It is also worth considering the role of international coordination in the collection of materials from long-cores or materials from seafloor based coring and drilling systems. In the 1990's and early 2000s some researchers were able to collect long (>40 m) piston core materials off the French research vessel, the R/V *Marion-Dufresne* through the coordination of the IMAGES program, which is no longer active. The Korean Polar Research Institute (KOPRI) Research Vessel Ice Breaker *Araon ("All Seas")* is currently undergoing a third ocean trial of its long-core system, which was originally designed by the group led by Jim Broda (WHOI) and is very similar to the WHOI Long-core System that was installed on the recently retired R/V *Knorr*. In addition to these two long-coring systems, many research institutes in around the world have standard (20-25 m) jumbo piston coring systems in routine operation.

Although international collaborations have often been fruitful, they do not solve the problem we are facing of reduced access to reliable standard jumbo piston coring and long-coring facilities for the U.S. science community. While an individual investigator may gain access to materials through a collaborative effort with scientists from other countries, the U.S. community as a whole typically does not gain access to the collected core material afterwards. While the U.S. core repositories serve scientists from any country with a valid sample request, the international core repositories generally do not have reciprocal open access policies for U.S. scientists. The responses on the survey suggest that access to material from foreign repositories is often limited to direct collaborators of scientists from those institutions, often U.S. scientists who may have a special technique or approach that does not overlap with the capabilities of the nation that collected the cores.

In short, if the U.S. is to retain a leadership role in the marine geosciences, it is essential that state-of-the-art coring technologies continue to be developed and supported within the U.S. research fleet.

Core repositories- incubators for future science

Under NSF policies, core materials returned to land provide a resource to the entire community of scientists, not only to the PI(s) of the cruise. In practice, open access to archived sediment cores works well; it is not uncommon for samples to be requested for decades after the cores were acquired, as new questions and methods come along. This pace is typically cumulative. For example, work on stratigraphy, dating, bulk geochemistry, etc. provides the framework for targeted sampling by other PIs that follows later. Overall, the survey revealed that the community is pleased with the level of service and access that they receive from the U.S. core repositories. While it is convenient to think of the repositories as core libraries, unlike books in a typical library, generally each core is unique, and every sample removed is a sample that is probably no longer useful to future researchers. Already collected cores are a unique resource, but they are a renewable resource only if there is regular collection of new cores. Core repositories can play a role in identifying regions with cores that are oversampled and need to be replenished with new material.

The excellent work done by U.S. core facilities can be further leveraged by policies that encourage automated core scanning (“multi-track sensor”) of all cores returned from sea, as this often provides very useful, cost-effective data that encourages use of core materials. Core repositories can also be encouraged to improve electronic data archiving so all relevant information, from site surveying to detailed sampling information, can be easily accessed on line in a way that links all relevant information to each core.

Appendix A: Coring Needs Survey and Results

Appendix B: Workshop Agenda

References

Augustin, L., C. Barbante, P. R. F. Barnes, J. M. Barnola, M. Bigler, E. Castellano, O. Cattani, J. Chappellaz, D. DahlJensen, B. Delmonte, G. Dreyfus, G. Durand, S. Falourd, H. Fischer, J. Fluckiger, M. E. Hansson, P. Huybrechts, R. Jugie, S. J. Johnsen, J. Jouzel, P. Kaufmann, J. Kipfstuhl, F. Lambert, V. Y. Lipenkov, G. V. C. Littot, A. Longinelli, R. Lorrain, V. Maggi, V. Masson-Delmotte, H. Miller, R. Mulvaney, J. Oerlemans, H. Oerter, G. Orombelli, F. Parrenin, D. A. Peel, J. R. Petit, D. Raynaud, C. Ritz, U. Ruth, J. Schwander, U. Siegenthaler, R. Souchez, B. Stauffer, J. P. Steffensen, B. Stenni, T. F. Stocker, I. E. Tabacco, R. Udisti, R. S. W. van de Wal, M. van den Broeke, J. Weiss, F. Wilhelms, J. G. Winther, E. W. Wolff, M. Zucchelli, and E. C. Members (2004), Eight glacial cycles from an Antarctic ice core, *Nature*, *429*(6992), 623-628.

Herbert, T. D., L. C. Peterson, K. T. Lawrence, and Z. H. Liu (2010), Tropical Ocean Temperatures Over the Past 3.5 Million Years, *Science*, *328*(5985), 1530-1534.

Kallmeyer, J., R. Pockalny, R. R. Adhikari, D. C. Smith, and S. D'Hondt (2012), Global distribution of microbial abundance and biomass in subseafloor sediment, *Proceedings of the National Academy of Sciences of the United States of America*, *109*(40), 16213-16216.

Keigwin, L. D., J. P. Sachs, Y. Rosenthal, and E. A. Boyle (2005), The 8200 year BP event in the slope water system, western subpolar North Atlantic, *Paleoceanography*, *20*(2), doi: 10.1029/2004PA001074.

Keigwin, L. D., and C. H. Pilskaln (2015), Sediment flux and recent paleoclimate in JordanBasin, Gulf of Maine, *Cont Shelf Res*, *96*, 45-55.

Koutavas, A., and S. Joanides (2012), El Nino-Southern Oscillation extrema in the Holocene and Last Glacial Maximum, *Paleoceanography*, *27*.

Lamy, F., R. Gersonde, G. Winckler, O. Esper, A. Jaeschke, G. Kuhn, J. Ullermann, A. Martinez-Garcia, F. Lambert, and R. Kilian (2014), Increased Dust Deposition in the Pacific Southern Ocean During Glacial Periods, *Science*, *343*(6169), 403-407.

Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic delta O-18 records, *Paleoceanography*, *20*(1).

Lund, D. C., J. F. Adkins, and R. Ferrari (2011), Abyssal Atlantic circulation during the Last Glacial Maximum: Constraining the ratio between transport and vertical mixing, *Paleoceanography*, *26*.

Luthi, D., M. Le Floch, B. Bereiter, T. Blunier, J. M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, and T. F. Stocker (2008), High-resolution carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, *453*(7193), 379-382.

Mackintosh, A., N. Golledge, E. Domack, R. Dunbar, A. Leventer, D. White, D. Pollard, R. DeConto, D. Fink, D. Zwartz, D. Gore, and C. Lavoie (2011), Retreat of the

East Antarctic ice sheet during the last glacial termination, *Nature Geoscience*, *4*(3), 195-202.
Roy, H., J. Kallmeyer, R. R. Adhikari, R. Pockalny, B. B. Jorgensen, and S. D'Hondt (2012), Aerobic Microbial Respiration in 86-Million-Year-Old Deep-Sea Red Clay, *Science*, *336*(6083), 922-925.
Twichell, D. C., J. D. Chaytor, U. S. ten Brink, and B. Buczkowski (2009), Morphology of late Quaternary submarine landslides along the US Atlantic continental margin, *Marine Geology*, *264*(1-2), 4-15.

Coring Needs Workshop
National Science Foundation
May 28-29, 2015
Agenda

Thursday, May 28

0830-0900 Coffee and breakfast

0900 Introduction (Major)
Why do we need this report? What are the decisions facing NSF? What is the history that has brought us here?

0920 UNOLS Vessel Replacements (Holik)
What are the plans for fleet replacement? What are coring capabilities of new and planned ships?

0940 Questions for NSF

1000 OSU Piston Coring Facility (Pisias or Walczak)
What are current capabilities and concerns/needs for the future?

1020 Coffee break

1040 WHOI Long Core (Broda).
What were capabilities as configured on the Knorr and needs for future deployment?

1100 Sea floor based drilling (Adkins)
Describe the systems and their capabilities and limitations

1120 Decadal Survey of Ocean Sciences (Mix)

1140 Discussion

1200-1300 Break for Lunch

1300 Science Accomplishments and Future Directions (Lynch-Stieglitz or Keigwin)
Summary of scientific accomplishments and future goals submitted by participants in advance of meeting and from survey results.

1330 Science Accomplishments and Future Directions Highlights Part I
Four 15 minute presentations of exciting science using piston/long coring.

D'Hondt: Deep Biosphere
Driscoll: Paleoseismology

Hill: Slope Failure
Polissar: Vegetation and hydroclimate from organic proxies

1430-1440 Coffee break

1440 Future Science Directions Discussion (What/where/how deep/how long are we likely to want to core in the next 10 years?)

1540 Outline of Part I of Workshop Report: Scientific Accomplishments and Future Directions
Present and discuss draft/outline of Part I of report. Writing assignments to complete or add sections

1610-1730 Writing time for Part I of Workshop Report

Friday May 29

0830 Coffee

0900 Science-Driven Coring Needs Discussion (Facilities needed to match the science: length of cores, water depths, types of sedimentary environment, drilling vs. coring quality of material, surveying and geophysics support for siting cores, etc.)

1000 Science Accomplishments and Future Directions Highlights Part II
Cronin: Chesapeake Bay Sea Level
Keigwin: High Res N. Atlantic Paleoceanography

1030-1045 Coffee Break

1045 Demand for Science-Driven Coring Discussion (past and projected demand, strategies to increase demand and broaden participation, models to support coring and maintenance of technical expertise, etc.)

1200-1300 Lunch Break

1300 Alternative Paths Discussion (outsourcing, international collaboration, etc.)

1330 Part II of Workshop Report: Science-driven Coring Needs
Presentation of outline and writing assignments
Writing time

1530 Final presentation and discussion of draft

1630 Adjourn